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INSTITUTE FOR PUBLIC POLICY
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NEW ENERGY TECHNOLOGIES:

A POLICY FRAMEWORK FOR MICRO-NUCLEAR TECHNOLOGY

SMALL INNOVATIVE REACTOR DESIGNS – USEFUL ATTRIBUTES AND STATUS OF TECHNOLOGY

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Abstract

Design and performance characteristics are examined of four representative Small Innovative Reactors (SIRs) – IRIS, PBMR, 4S and ENHS. It is shown that SIRs have a number of useful attributes, including the following:

- Reduced number of components and design simplicity.
- High degree of modularity, with complete modules fabrication and assembly in factory.
- Elimination of severe accidents by design leading to enhanced safety.
- Simplified operation and maintenance.
- Enhanced proliferation resistance.
- Close match between demand and supply of electricity.
- Short construction time.
- Long plant life.
- Investment protection.
- Cost effective approach to technology development.

It is concluded that SIRs have significant differences in their design features and performance characteristics from large size reactors that justify taking a thorough examination of the desirability of their commercialization.

1. Introduction

Many small reactor designs have been proposed for development in recent years. These vary from downsizing conventional LWR designs to innovative designs using different coolants. A compilation of these reactors can be found in references 1 and 2. These include reactors cooled by water, by helium, by sodium, by lead or lead-bismuth, and by molten-salt. Some of these reactor concepts have innovative features that may make them more attractive for application in developing countries than the reactors that have been developed to date. The primary purpose of this paper is to show that Small Innovative Reactors (SIRs) have significant differences in their design features and performance characteristics from large size reactors that justify taking a close examination of the desirability of their commercialization. Another objective of this paper is to describe the state-of-art of the technology of a number of SIR designs and to identify the R&D required before their commercialization.

Four small innovative reactor design concepts are considered; one reactor per coolant technology:

- IRIS[3,4] – A novel PWR concept with steam-generators integrated within the reactor pressure vessel.
- PBMR[5,6] – The modular graphite-moderated helium-cooled reactor that uses direct cycle gas turbine.
- 4S[7,8] – A sodium cooled modular fast-reactor that is designed to operate for up to 30 years without refueling.
- ENHS[9,10] – A modular Pb-Bi or Pb cooled reactor that is designed to function as a "nuclear battery" – it is shipped to the site fueled and replaced by a new module after 20 years of full power operation (EFPY). All these SIRs can be considered Generation-IV reactors. They will require R&D and testing prior to their being available commercially. In fact, R&D of IRIS and ENHS, as well as of certain aspects of PBMR, are being actively pursued in the framework of the U.S. DOE NERI program.[11]

Table 1 summarizes some general information concerning the reference SIRs while Table 2 brings more detailed technical data for these reactors. Although molten-salt fueled and cooled reactor technology has a number of very promising features, no sufficient R&D of molten-salt reactor technology has been pursued to justify their inclusion in the present review.

Table 1. Reference SIRs Considered

Characteristic	Reactor Type			
	IRIS	**PBMR**	**4S**	**ENHS**
Primary/secondary coolant	H_2O	He	Na/Na[(a)]	Pb-Bi/Pb-Bi[(b)]
Thermal power (MW_{th})	300-1000	265	125	125
Electric power (MW_e)	100-335	100-110	50	50
Developer	W+MIT+ UCB+int.	ESKOM	TOSHIBA+ CRIEPI	UCB+ANL+ LLNL+W+int.
Design status	Conceptual	Preliminary	Conceptual	Pre-conceptual

[a] There is also a version that uses Pb-Bi coolant.
[b] Can use also Pb or Na.

Table 2. Selected Characteristics of Reference SIRs

Characteristic	Reactor type			
	IRIS	**PBMR**	**4S**	**ENHS**
No. coolant systems	2	1	3	3
Thermodynamic working fluid	H_2O	He	H_2O	H_2O
Primary coolant in/out temp (^oC)	292/330	350/900	400/550	400/550
Primary coolant pressure (MPa)	15.5	7	1	1
Thermodynamic cycle	Rankine	Brayton	Rankine	Rankine
Thermodynamic efficiency (%)	35	45	40	42
Fuel type	oxide	oxide/carbide	metallic	metallic
Preferred fissile material	^{235}U	^{235}U	Pu	Pu
Fissile enrichment ($^w/_o$)	5[a]	~8	~20	~10
Fuel replacement intervals (y)	5[a]	continuous	15-30	20
Reactor vessel (RV) height (m)	23	16	23	20
Reactor vessel diameter (m)	6.5	11	2.5	3.2
RV module completed in factory?	No	No	No[b]	Yes
Reactor fueled in factory?	No	No	No[b]	Yes
Reactor can be fueled on site?	Yes	Yes	Yes	No
Spent fuel removed from RV?	Yes	Yes	Yes	No
Can RV be opened on site?	Yes	Yes	Yes	No
Do pipes connect RV to plant?	Yes	Yes	Yes	No
Startup after modules arrival (y)	~2	~2	~1	~1/12
Time to replace RV (y)	N/A	N/A	~2	~1/6
Number of safety elements	~20	18	1	1
Number of control elements	~20	6	6	6
Number of pumps inside RV	6	2	1	0
No. of heat-exchangers inside RV	8	0	1	0

[a] Core designs having higher enrichment that can operate without refueling for ~10 years are being investigated. The implementation of such reload cores will require testing and licensing extension.
[b] Yes, for a lead-bismuth cooled version of 4S reactor that has recently been suggested.

The approach used for conveying the message that the development of SIRs might make nuclear energy available to a broader group of users, in particular to users in developing countries, is the following: First, potential attractive attributes of SIRs are identified. Then illustrations of how each of the identified attributes can be achieved are outlined. For the sake of these illustrations we'll examine the design approach used in one or more of the reference SIRs. The specific SIRs selected for illustrating a specific attribute are selected based on convenience for conveying a given message. Use of a given SIR for illustrating a given attribute is not to imply that this particular SIR is better than all other SIRs as measured by the attribute considered. Likewise, we are not attempting in this paper to rank the reference SIRs in any order of priority or preference.

Section 2 identifies the special attributes of SIRs while Sections 3 through 12 illustrate each of the 10 special attributes. In Section 13 we discuss the possibility that SIRs will be economically viable. The description of the present state of development of the 4 reference SIRs is given in Section 14 while Section 15 gives a preliminary assessment of the R&D program required for their commercialization. Recommendations are given in Section 16.

2. Special Attributes of SIRs

Extensive use of nuclear power has been limited to a few of the developed countries and even the growth of its use in these countries has been slowed. There are several key reasons contributing to this limited use and growth:

- Concerns about safety.
- Concerns about nuclear waste.
- Concerns about proliferation of technology related to nuclear explosives.
- The high cost and large financial risk associated with constructing large reactors.
- The need to have a large power grid to accommodate large reactors.
- The need for a large, specially trained, staff for operations and maintenance.

The low power level and small physical size of SIRs enable their designs to incorporate attributes that address some of the identified reasons for the limited use of nuclear power. We shall consider ten of these attributes:

- Simplified design.
- High degree of modularity, with complete modules fabrication and assembly in factory.
- Elimination of severe accidents by design leading to enhanced safety. Also, safety features can be demonstrated in a full-scale reactor.
- Simplified operation and maintenance.
- Enhanced proliferation resistance.
- Close match between demand and supply of electricity.
- Short construction time.
- Long plant life.
- Investment protection.
- Cost effective approach to technology development.

3. Simplified Design

There are several reasons that make it possible to reduce the number of components and/or simplify the design of the Nuclear Power Plant (NPP) by reducing its capacity. We shall identify them by way of several illustrations.

3.1 IRIS

By integrating the steam generators, coolant pumps and pressurizer within the reactor vessel, the IRIS design eliminates the large piping loops that typically connect these components. This eliminates the possibility of large loss-of-coolant-accidents (LOCA). Combined with the large integral RV water volume, this also eliminates the need for SI accumulators and core makeup tanks to provide rapid and large water injection capability. The resulting Nuclear Steam Supply System (NSSS) can be designed to be significantly more compact and housed in a containment of a significantly smaller specific volume. Figure 1 compares[12] the containment volume of IRIS with that of AP-600[13] – the most advanced Pressurized Water Reactor (PWR) design that has been certified by the U.S. Nuclear Regulatory Commission.

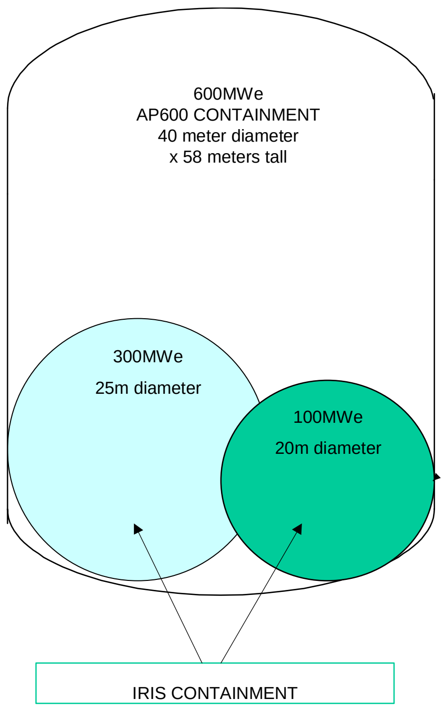

Fig. 1 Comparison of IRIS Containment With that of AP-600[13]

A couple of IRIS reactor designs are considered in Figure 1: one for 100 MW_e while the other for 335 MW_e. It is estimated that the specific volume of the containment of the 335 MW_e IRIS is only 22% that of AP-600! That is, the volume of the containment of one AP-600 PWR generating 600 MW_e is 4.5 times larger than the combined volume of the containment of two IRIS reactors of 335 MW_e each. Despite being of a small specific volume the IRIS, containment is designed to withstand the pressure buildup in case of a small to medium LOCA by virtue of its smaller diameter and spherical shape.

3.2 PBMR

Figure 2 compares the major components of two power plants based on a graphite-moderated, He-cooled high-temperature reactor - one uses a steam power plant and the other uses a gas turbine (GT) power plant for converting the fission-generated thermal energy to electricity. The specific illustration is for the GT-MHR reactor under development by General-Atomics.[14] The general layout and number of components of the PBMR is similar to that of the GT-MHR.

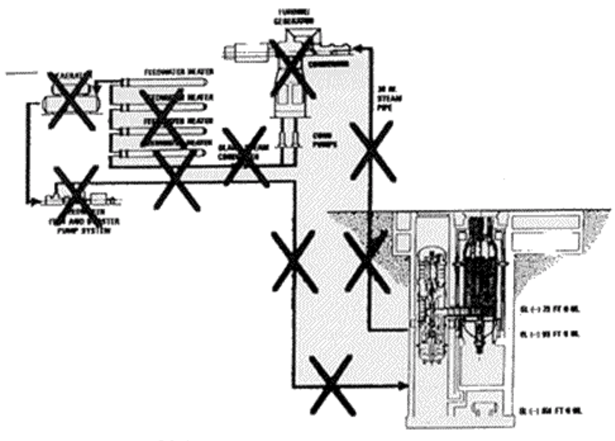

Fig. 2 The Gas-Turbine Modular Helium-Cooled Reactor (GT-MHR) Plant Schematics Versus Plant Schematic of the Modular High Temperature Gas-Cooled Reactor (MHTGR) that used the same reactor but a steam-driven Rankine, rather than a gas-driven Brayton energy conversion system.[15]

It is observed that by replacing a conventional steam power plant by a direct-cycle GT power plant it is possible to significantly reduce the number of components and the overall size of the power plant. The size reduction is reflected in reduced land area required for a given capacity power plant as well as reduced total weight of materials that go into the power plant construction. In addition to size reduction, the conversion to a GT implies that a larger fraction of the construction effort is to be done in factory, shorter construction time and higher thermodynamic efficiency.

3.3 4S

Table 3 compares the specific weight of materials that go into the construction of the 4S reactor versus that required for the construction of SUPERPHENIX: a large size sodium-cooled fast reactor. The specific weight is a measure of the capital investment per installed electricity generating capacity as measured, say, in $/KWe. It is found that although the installed capacity of the 4S reactor is only ~ 4% of that of SUPERPHENIX, its specific weight is smaller by nearly 20%. This is due to many simplifications in the design of the 4S reactor that were made possible by virtue of its small size. Among the design simplifications are the following:

- Elimination of upper core structure by using reflector segments instead of control rods.
- Use of only few simple drives for control and safety rods.
- Elimination rotating plug for refueling.

- Elimination of concrete neutron shield at the structure roof due to use of thick sodium layer above core.
- Elimination of A-Class control room; control can be done autonomously.
- Reduction of required emergency power by relying on decay heat removal by natural circulation.

More recently TOSHIBA designed a new version of the 4S reactor, referred to L4S[16] that uses Pb-Bi instead of Na for the primary coolant and eliminates the second Na coolant loop altogether. The resulting L4S reactor has fewer components and is significantly more compact, for the same power output, than the 4S reactor considered above – see Fig. 3.

Table 3. Comparison of Specific Weight of the 4S Versus SUPERPHENIX Reactors

		Reactor Type	
	Item	**SPX (1200MW$_e$)**	**4S (50MW$_e$)**
Weight (tons):	Reactor vessel	400	35
	Guard vessel	265	33
	Reactor internals	960	21
	Deck structure	1800	10
	Inner shield	1157	68
	IHX	592	45
	Primary pump	480	12
	Containment	700	(IHX enclosure)
	Total	**6345**	**224**
Specific weight (tons/MW$_e$)		5.3	4.4

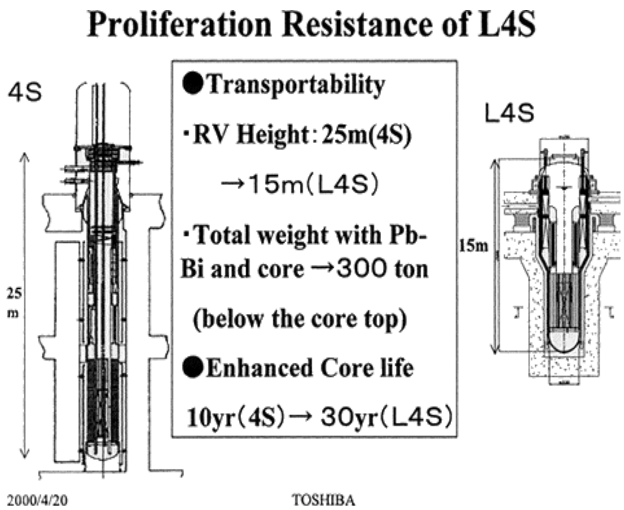

Fig. 3 Comparison of L4S and 4S Reactors.

3.4 ENHS

Figure 4 shows, very schematically, the so-called "nuclear island" of the Encapsulated Nuclear Heat Source reactor. The ENHS module is inserted into the center of the secondary coolant vessel. Eight steam generators are also immersed in the secondary coolant vessel, surrounding the ENHS module. Both the primary coolant (located inside the ENHS module) and the secondary coolant (located inside the reactor pool) flow by natural circulation. That is, there are no mechanical or other types of pumps that force the coolant to circulate. The fission-generated heat is transferred from the primary to the secondary coolant through the wall of the ENHS module vessel that is of a special design. By virtue of this design there are no pipes and no valves in the nuclear island. Moreover, the fuel is loaded into the ENHS module in the factory and the module is designed to operate for 20 EFPY (effective full power years) without refueling. At the end of its life the ENHS module is replaced by a new module. Consequently, the ENHS reactor does not have any fuel handling hardware. As the ENHS module is disposable, it does not have a radiation shield to protect the vessel from neutron-induced radiation damage. As the ENHS reactor is designed to avoid severe accidents, it does not need any special safety systems excluding one safety element, six control elements and a completely passive reactor vessel air-cooling system. In summary, the ENHS nuclear island is designed to have small number of relatively simple and robust components.

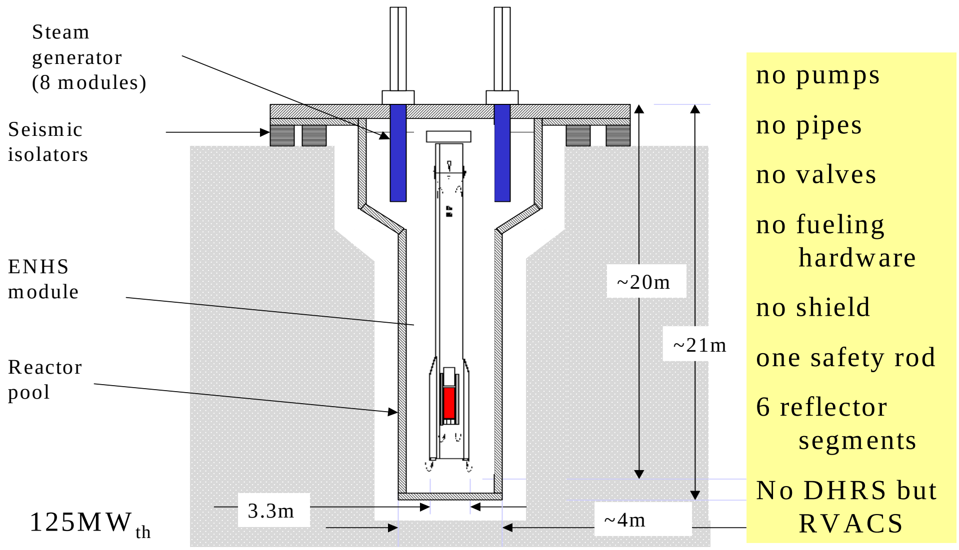

Fig. 4 General Layout of the Nuclear Steam Supply System of a Power Plant Based on a Single ENHS Module

An illustration of the difference between the design of an ENHS module (left) and a common design of a liquid-metal cooled reactor vessel is brought in Fig. 5. The ENHS module is significantly simpler; it does not have pumps and decay-heat removal system (DHRS) and no pipes are connected to it. Its intermediate heat exchanger (IHX) is integrated within the module vessel walls.

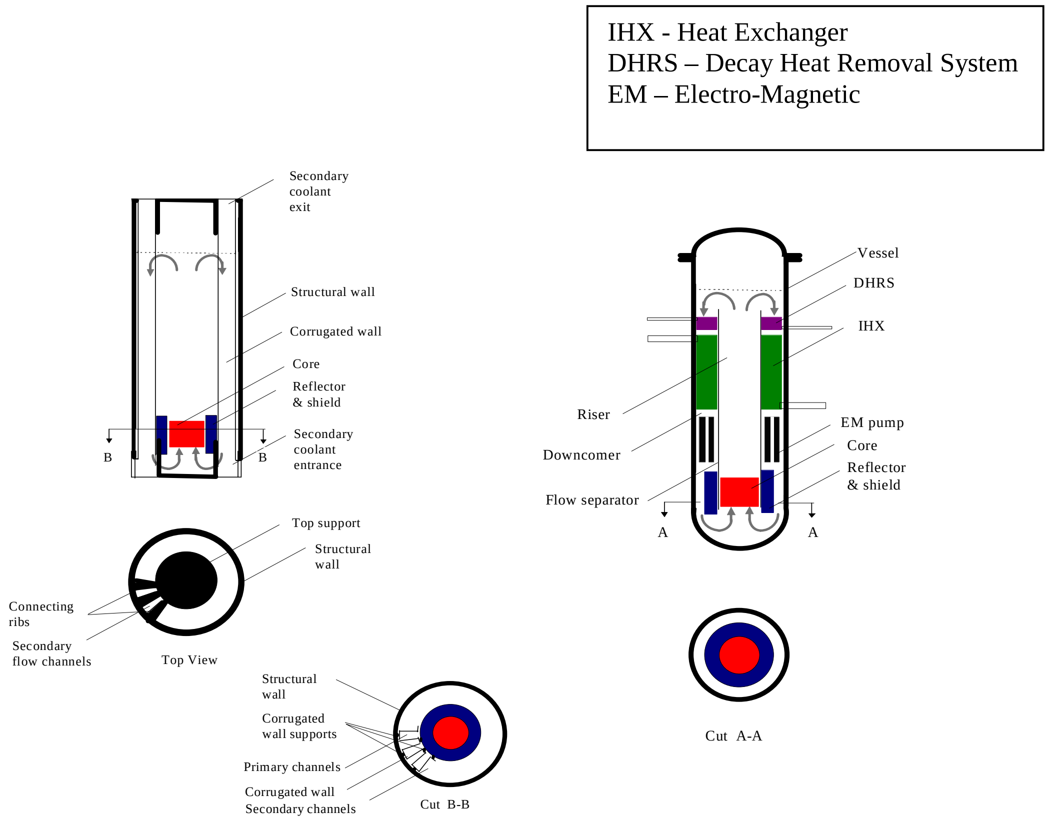

Fig. 5 A Comparison Between the ENHS Module and a Common Fast Reactor Design Approach

3.5 Discussion

The majority of the simplifications in the design of SIRs, illustrations of which were presented in this section, are inherently connected with the small size of the reactor. Following are a number of specific examples of this connection:

- The IRIS reactor concept features integration of the steam-generators within the reactor vessel coupled with a low power density core. The latter feature is dictated by the requirements for long core life and enhanced safety. As the outer dimensions of the reactor vessel are constrained by fabrication limitations as well as by transportation limitations, the maximum power level the reactor can be designed to have is, approximately, 1000 MW_{th} (~335 MW_e).

- The power level of a PBMR is limited by the requirement for passive safety. In particular, by the requirement that the decay heat could be removed without any active cooling system while the fuel temperature does not exceed ~1600^{o}C. Above this temperature the ceramic coatings of the fuel particles do not provide adequate containment of radioactive fission products.
- The power level of the 4S reactor is limited by the requirement to have a long-life core that has a negative void coefficient of reactivity.
- The power level of the ENHS module is limited by the requirement of natural circulation along with the requirement that the temperature difference between the primary and the secondary coolants will not exceed approximately 50^{o}C.

4. High Degree of Modularity and Factory Fabrication

Key to reducing cost of nuclear systems is reducing the extensive time for on-site construction, assembly and equipment installation. SIRs, because of their reduced physical size, simplicity and integration of equipment permit much of this work to be completed in the factory. In the extreme case, ENHS includes installation and ultimately removal of the fuel in a factory environment. Not only does this reduce cost but it also provides for repeated use of skilled labor and an opportunity for improvement in quality control. The modules completed at the factory have only few interfaces to be connected to installation at the site.

The extent of factory assembly will vary with the specific SIR design, but all systems focus on maximizing the factory assembly of the modules and minimizing the on-site tasks required for integrating them into a complete plant. Following are several illustrations.

4.1 <u>PBMR & GT-MHR</u>

The PBMR that uses direct-cycle gas turbine consists of three major modules: the reactor module, the turbo-generator module, and the circulator module. This is similar to the GT-MHR layout of which is shown in Fig. 2 (the right-hand side), except that the circulators are separated from the turbo-generator assembly. The turbo-generator module includes, in addition to the turbine and the generator, a recuperator, helium circulators (in separate vessels for PBMR), and pre-coolers. The reactor module is large – similar to the size of the reactor vessel of a BWR. Hence, the module cannot be completely factory fabricated. The reactor module of the PBMR also needs to be interfaced with an on-line refueling system. Such a system is illustrated in Fig. 6 (right) for the MIT conceptual design of the PBMR layout of which is also shown in Fig. 6 (left). The MIT PBMR uses indirect cycle and needs an IHX module in between the reactor and turbo-generator modules. In the PBMR of Ref. 5 a helium circulator rather than an IHX module interfaces between the reactor and the turbo-machinery module and the turbo-machinery module is vertically aligned.

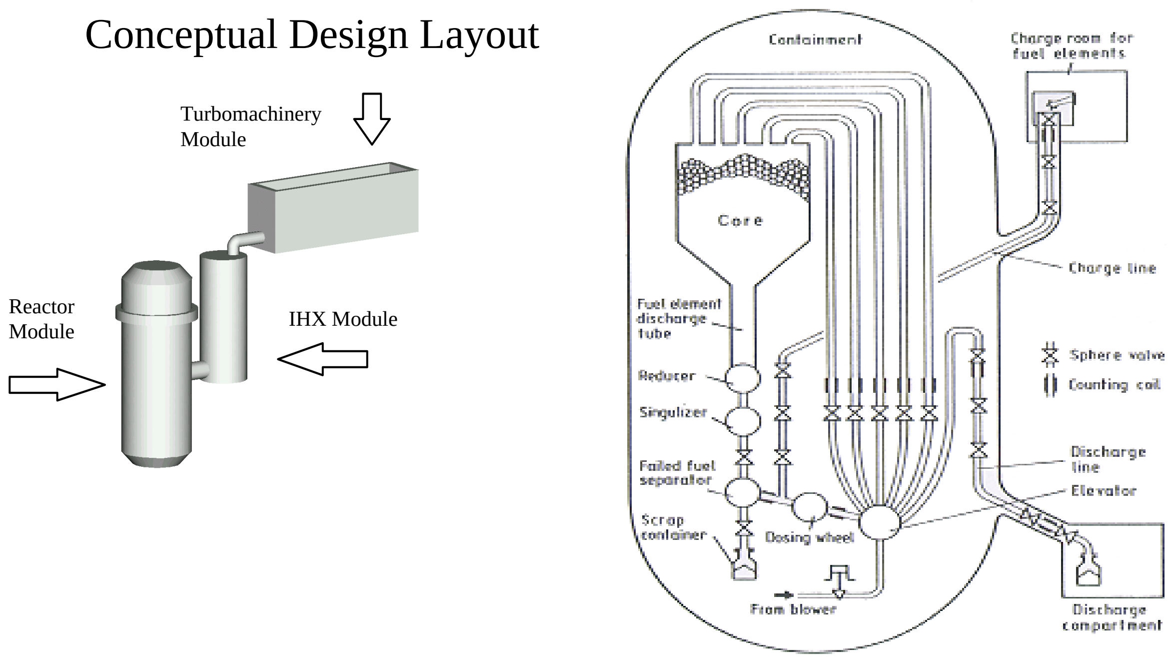

Fig. 6 Conceptual Design Layout of the MIT Indirect-Cycle PBMR (left) and of its On-Line Fuelling System (right)[17]

4.2 4S and ENHS

Both the 4S and ENHS reactor vessel modules can implement a high level of factory fabrication. In the case of ENHS it is anticipated that most of the plant could be delivered to site in as few as four types of modules: the reactor vessel module, the steam generator modules, the power conversion module and the control room module. Each of these would have interface connections, including instrumentation and control and power cabling that would simplify and reduce the on-site time to assemble the integrated plant. Moreover, the ENHS reactor vessel module has used as a design objective the complete fabrication and fuelling within the factory. The ENHS steam generators are relatively simple stand-alone modules (See Fig. 4); they are not connected to the reactor vessel by pipes. Hence, they are simple to install, inspect and replace.

5. Elimination of Severe Accidents by Design -- Enhanced Safety

Whereas currently operating power reactors cope with accidents via active safety systems, Generation IV reactors are attempting to eliminate severe accidents by design and to cope with other accidents via passive means. SIRs are uniquely capable of meeting these safety design goals. One reason for this capability is the relatively large surface area – to – volume ratio of their core. This enables removal of decay heat by passive means without heating up of the fuel or clad to damaging temperatures. Following are three illustrations.

5.1 IRIS

Table 5 summarizes the major differences in the approach to the design of IRIS versus conventional PWRs as far as safety implications are concerned.[12] One of the most important unique design feature of IRIS – the integration of all of the primary coolant loops (including the steam generators) within the reactor vessel, eliminates the possibility of a large Loss Of Coolant Accident (LOCA). Designing the IRIS primary loop (contained in the reactor vessel) to have a high degree of natural circulation greatly reduces the probability for a Loss Of Flow Accident (LOFA). The net result is that IRIS can be subjected to only one severe (so called Class IV) accident versus 8 in AP600.

5.2 4S

The 4S reactor design also eliminates the possibility of a LOCA, as all the primary coolant is inside the reactor vessel. Two additional features that contribute to the LOCA elimination are:

1. The reactor coolant is at a close to atmospheric pressure thus minimizing the probability of a breach in the reactor vessel.
2. The reactor vessel is located inside a silo, thus even a breach in the vessel will not result in uncovering of the core.

The above features are also shared by larger liquid metal cooled reactors (LMRs), such as S-PRISM.[18] However, relative to larger LMRs, the 4S reactor has a significantly larger core and reactor vessel surface area to volume ratio. This, combined with a negative temperature feedback, give the reactor the ability to maintain its integrity even under the most severe conceivable accidents, such as loss of power or loss of heat sink, without use of any active systems for reactor shutdown or for heat removal. The reactor has very small excess reactivity throughout life and can tolerate insertion of maximum available excess reactivity without a forced shutdown (“scram”).

Table 5. Approaches to IRIS Design that have Safety Improvement Implications[12]

IRIS Design Characteristic	Safety Implication	Related Accident	Disposition
Integral reactor configuration	No external loop piping	Large LOCAs	Eliminated
Tall vessel with elevated steam generators	High degree of natural circulation	LOFAs (e.g., loss of all pumps)	Either eliminated (full natural circulation) or made easier to mitigate (high partial natural circulation)
	Can accommodate internal control rod drives	Reactivity insertion due to control rod ejection	Can be eliminated
Low pressure drop flow path and multiple (6) reactor cooling pumps	5 pumps keep adequate core cooling; no core damage occurs	LOFAs (e.g., reactor cooling pump shaft break or rotor seizure)	Condition IV accident eliminated
High pressure steam generators, piping, and valves	Primary system cannot over-pressure secondary system	Steam generator tube rupture	Mitigated simply by automatic steam and feed line isolation
	No steam-generator safety valves required	Steam and feed line breaks	Creditable breaks less probable; no safety valve failure & steam line break accident
Long life core	No partial refueling	Refueling accidents	Reduced probability
Large water inventory inside vessel	Slows transient evolution Helps to keep core covered	Small-medium LOCAs	Core remains covered with no safety injection
Reduced size, higher pressure containment	Reduced driving force through primary opening		
Inside the vessel heat removal			

5.3 ENHS

The ENHS reactor offers a number of unique safety attributes even beyond those of the 4S reactor. These include the following:

1. No possibility for LOFA. This is because the coolant circulates by temperature induced density differences rather than by forced circulation.
2. The total heat capacity of the primary and secondary coolants is very high.
3. The excess reactivity built into the core is even smaller.

An additional unique safety feature of the ENHS reactor is that there is no handling of fuel at all inside the host country; the fuel is always enclosed inside a seal welded vessel. During transportation the fuel is imbedded in solidified lead or lead-bismuth, making the probability of nuclear accidents during transportation very low, if not eliminating such accidents all together. The low frequency of fueled module replacements – once every 20 EFPY, also contributes to the superb safety in fuel handling and transportation.

5.4 Summary

Certain SIRs can be designed to have superb safety characteristics such that are based entirely on the laws of physics. That is, without reliance on operation of mechanical or electrical components such as pumps, valves, motors, generators etc. No postulated accident was identified that could impair the integrity of their fuel or of the reactor structure. No operator intervention is necessary. As a consequence, there is no need for any emergency-planning zone outside of the fence of the power plant that is based on these SIRs. Large reactors can be designed to be very safe, but they cannot match the safety attributes of small reactors. By enabling to completely eliminate fuel handling in the host country, SIRs also can offer enhanced proliferation resistance and unique protection against accidents during refueling and fuel transportation.

6. Simplified Operation and Maintenance

SIRs can be designed to be significantly simpler to operate and to maintain than large-scale reactors. One reason for this is the simplification in design and reduced number of components that is addressed in Sec. 3. Another reason is the very simple core and control system they can be designed to have. Yet another reason is their superb safety and its dependence on natural physical phenomena rather than on proper function of mechanical and electrical components. Additional reasons are reactor specific. Illustrations for the 4S and ENHS reactors follow.

6.1 <u>4S</u>

The 4S reactor core is very slender – small diameter (~80 cm) and long fuel (~400 cm). There is a single safety element at the radial center of the core. The reactivity control is done by axial movement of an annular cylindrical shell that surrounds the core. This shell is made of six segments, for redundancy, and is referred to as the "reflector." A special drive mechanism continuously raises the reflector at a very slow constant rate of ~1mm per day. Raising the reflector introduces positive reactivity that is used to compensate for the negative reactivity effect of fuel burnup. Load variations are accomplished autonomously – via temperature feedback. Changes in the flow rate of water through the turbine plant can induce up to 10% variation in the reactor power. By adjusting the secondary sodium flow rate as well it is possible to set the power level anywhere between 15% and 112% of nominal. Following reactor startup, no operator need be involved in the reactor reactivity control. In case of larger than 10% variations in the power demand, operators need to adjust only the secondary sodium flow rate.

6.2 <u>ENHS</u>

The ENHS adopted the reactivity control systems of the 4S reactor but is even simpler to operate and to maintain. This is due to the following reasons:

1. There is only very small change in reactivity due to fuel burnup, so that there is no need for a continuous withdrawal of the reflector and, correspondingly, there is no much shift in the axial power distribution.
2. There are no pumps or valves in the nuclear island directly associated with the reactor operation.
3. The reactor has a very wide range of autonomous load following capability; the ENHS power level can adjust itself to the power drawn from the turbine without any operator intervention.

4. There is no fuel handling on site.
5. The ENHS module is disposed of at the end of the core life of ~ 20 EFPY. Hence, there is no much concern about deterioration of components due to radiation damage. The reactor vessel is not to be opened on site.
6. There is easy access to inspect the steam generators and it is relatively easy to repair or even replace them.

Both the 4S and ENHS power plants will require staff for operating and maintaining the balance-of-plant (BOP – the plant systems that are not part of the nuclear island), for plant security, for radiation monitoring etc. But very few staff members are required to have high level of expertise in reactor theory. It is anticipated that the needed staff is less then 50 for a single-module ENHS power plant (50 MW_e) and less than 100 for a plant having ten ENHS modules (500 MW_e). For comparison, the staff of the two 1100 MW_e PWR power plant in Diablo Canyon, California, is approximately 1300.

7. Enhanced Proliferation Resistance

SIRs have special attributes of that make them more proliferation resistant than conventional, large capacity nuclear reactors. These attributes include the following:

1. Low frequency of refueling.
2. Restricted access to fuel.
3. Restricted access to neutrons.
4. Elimination of the host country needs to construct facilities that could be used for clandestine production of strategic nuclear materials.

These attributes are illustrated by considering the ENHS, which conceptually provides all these attributes. The other SIR designs provide one or more of these attributes and also improve the proliferation resistance over the currently available commercial NPPs.

7.1 No Access to Fuel

The combination of long-life core and nearly constant multiplication-factor (k_{eff}) makes it possible to eliminate on-site refueling altogether. The ENHS module is designed to be factory fueled and to be disposed of, or recycled, after 20 EFPY of operation. It is envisioned that the ENHS factories and possibly co-located recycling facilities would incorporate stringent international safeguards and security controls. The fuel is to be sealed inside the ENHS module from the time the module leaves the factory until the spent module is returned to the waste disposal site or to a regional or international recycling center. It is envisioned that the ENHS power plants will not even have on-site hardware for refueling.

The lack of need for on-site fuel handling, combined with the relatively small number of components inside the ENHS module, enables designing the module in a way that will make it unnecessary to ever open. The components inside the module are robust and will be designed to operate reliably for 20 EFPY without a need to access them. Thus we envision the ENHS module to have the fuel sealed inside a welded vessel that could serve as a disposal container or would only be recycled at a secure internationally controlled recycling center. Even if individuals in the client country were to break off the top cover of the ENHS vessel, they will not have access to the fuel, as the fuel is loaded from the bottom of the vessel. While in the pool the ENHS vessel is imbedded in Pb or Pb-Bi and its bottom is not accessible.

When outside the factory and outside of the reactor pool, the fuel is imbedded in solid Pb-Bi (or Pb) except for a short period of time after the removal of the spent ENHS module from the pool when the Pb-Bi (or Pb) will be in a liquid state. At that period of time the module structure and fuel will be highly radioactive, practically eliminating access to the fuel.

It is practically impossible to steal the ENHS module with the fuel: The module is ~20 m long and ~3 m in diameter and weighs ~ 300 tons. The fact that the fuel is shipped imbedded in solid Pb-Bi or Pb makes it even more difficult to steal the fuel; it will take long time and special mechanical and heating equipment to destructively “break the way” into the fuel. Any attempt to break into the module could be immediately detected by the IAEA by using automatically operating monitors that are connected to wireless transmission devices. The long time it will take even a trained team of people to break into the fuel will give the international community ample time to take measures to prevent diversion of the ENHS fuel.

7.2 No Access to Neutrons

There is no access to the neutrons in the client country. There are very few components inside the module; none requires maintenance. Hence, no need to open the module in the client country for operation and maintenance. Moreover, the module is sealed in the factory so that efforts to open it in the client country must be destructive and can be detected almost immediately. Even if there were a way to open the module in the client country undetected, it would be physically impossible to insert fertile material for irradiation into the core. This is because the fuel rods fill all the space inside the core barrel and there is no way to remove fuel from the top of the core. There is no blanket fuel in or around the core as is common in designs of sodium-cooled fast reactors. The current of neutrons outside of the ENHS module vessel is too low to be useful for any strategic material production application.

7.3 Radiation Barrier

Another unique feature of the ENHS is the possibility to seed in the core strong gamma-ray sources that could make a very effective radiation barrier to supplement the radiation that emanates from the fuel. This is because the fuel is loaded in the factory and is shipped to the site imbedded in Pb-Bi or Pb. Thus, after loading the fuel into the ENHS vessel and before pouring in the Pb-Bi or Pb it is possible to insert into the core, or its close vicinity, strong sources of gamma rays. After filling the module with Pb-Bi or Pb up to the top of the core, the radiation level outside of the ENHS module will be very low; it will not interfere with the shipment and installation of the ENHS module. However, if potential diverters will be trying to remove the Pb-Bi or Pb in order to get access to the fuel, they will be hindered by the high radiation field of the seeded radiation sources. It would require a very large hot cell and very complicated remote operations to gain access to the fuel.

7.4 No Facilities Suitable for Military Applications

Constructing and operating ENHS reactors will not give the country sensitive technologies that can be used for clandestine production of strategic nuclear materials. Specifically, no fuel fabrication or handling facilities are needed in the client country.

The need for such facilities has been attributed, in the past, to the need of the country to maximize its independence in energy supply. For reactors that need be refueled once every year or 18 months, as are all the commercially operating nuclear power reactors, fuel fabrication capability and spent fuel-handling capability certainly adds to the country's independence. However, SIRs such as the ENHS can offer long-term energy security (due to the very long life cores they can have) without acquiring fuel enrichment and spent fuel reprocessing capabilities.

8. Close Match Between Demand and Supply of Electricity

This attribute is inherently connected with the small capacity per reactor unit. It is being dealt with in other papers presented at this workshop.[19-23] This attribute could be of much interest also for energy producers in industrial countries. Past practice in industrial countries was to install large capacity NPPs, typically exceeding 1000 MW_e per unit. In certain countries, like Japan and France, the trend is to go to even larger units – 1500 MW_e and even higher. However, in the deregulated power industry recently established in many States of the USA, independent power producers are expressing their preference for small capacity units that will enable them to closely match supply to demand.[19-23]

Multi-SIR plants could provide an ideal answer to the electricity market that is being developed in industrial countries. Figure 7 is an illustration of the layout of a 1000 MW_e central power plant consisting of 10 PBMR units, as envisioned by the MIT PBMR group.[17] In this scheme each unit has its own energy-conversion system. There are common facilities such as control building and shops.

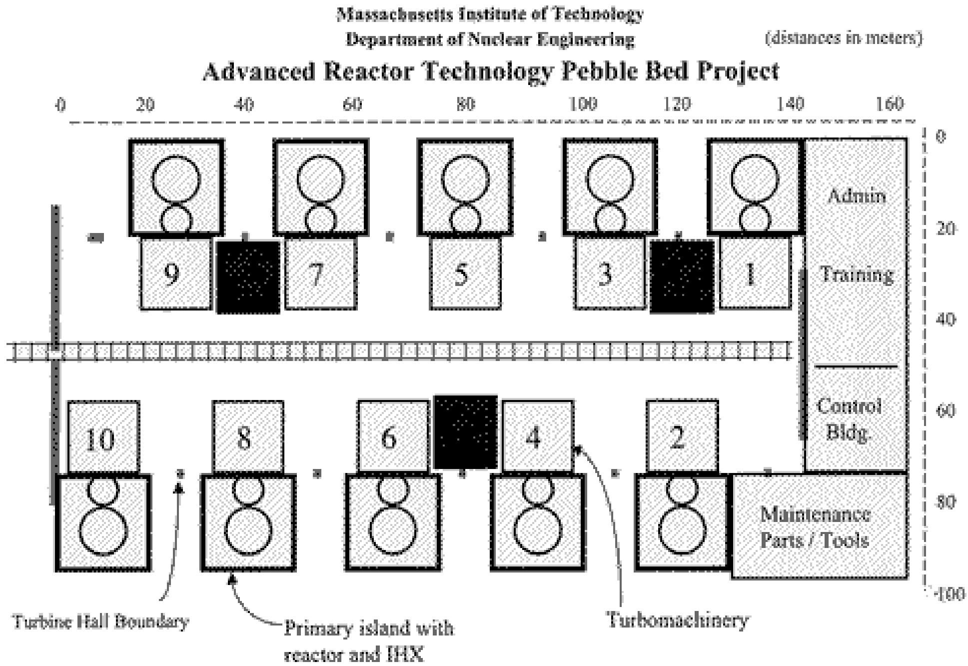

Fig. 7 A Schematic Layout of a 10-Unit PBMR Power Plant For a Total Capacity of 1000 MW_e[17]

An alternate approach to multi-unit central NPP is depicted in Fig. 8. Here there are 10 ENHS modules all inserted into one single pool, making a 500 MW_e power plant. The pool can be made out of concrete, as being proposed by Russians for large capacity lead-cooled reactors.[24] The inner side of the concrete need be thermally insulated (not shown in Fig. 8). The alumina pads proposed by the Russians[24] could possibly be used for this insulation. A single energy conversion system can be used for such a plant. There is much flexibility in sizing the multi-module plant capacity to the needs of the power producer.

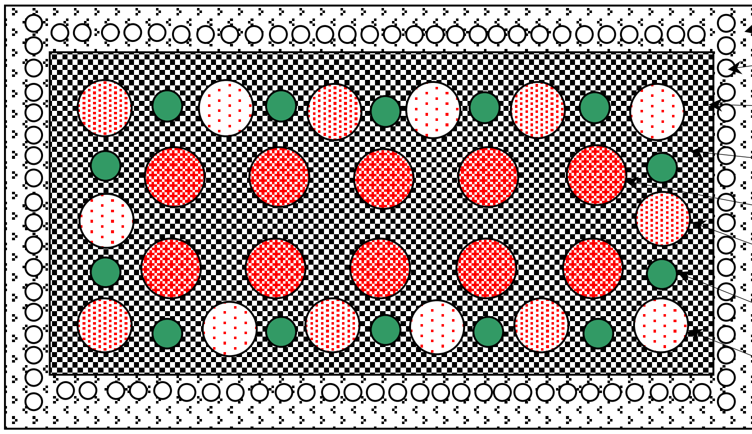

Fig. 8 A Schematic Horizontal View of a 10-ENHS Module Reactor Using Insulated Concrete Massive Structure for the Secondary Coolant Pool
(Not to scale)

An attractive attribute of either of the multi-SIR plant concepts is that they enable the power producer to get a close match between the generating capacity of the grid and the demand. This match is accomplished in small power increments, each involving relatively small investment. The addition of a unit can be done on a relatively short notice. This option means that capital need not be invested in excess capacity and in a deregulated market the potential for excess capacity depressing the power market need not be of concern.

9. Short Construction Time

Small reactor plants that have extensive assembly completed in factories will require much less site work than large reactor plants. This could be limited to completing the interfaces with the ultimate heat sink cooling systems, with the structural support and with the switchyard. The on-site construction activities can be scheduled such that they are completed at the time of delivery of the several modules needed to make the power plant.

Construction times for large nuclear plants are usually four to five years in the best situations, whereas it is possible to install gas turbine power plants in less than one year. It is projected that it should be possible with small nuclear plants to achieve an on-site construction time closer to the gas turbine power systems. Such a rapid installation is the result of reduced systems and simplified interfaces. Substantial cost savings should be realized from the rapid installation.

10. Long Plant Life

The design lifetime of conventional nuclear power plants used to be 40 years. Several plants in the USA have recently received from the Nuclear Regulatory Commission (NRC) license extension for additional 20 years. Owners of many of the other NPPs are planning to apply for life-extension. The incentive for life-extension is economic; it is very profitable to generate electricity in a plant that has already returned all the investment associated with its construction. Yet quite a number of NPP will be shutdown after 40 years of operation. This is because it is too expansive to make the modifications necessary to assure safe and reliable operation. In fact, a number of NPPs were shutdown before they even reached their designed life. This is because of the deterioration of one or more of their major components, usually the reactor vessel or steam generator.

SIRs, by virtue of their highly modular design, offer the possibility of running the NPPs significantly beyond even 60 years. It has been suggested[25] that their lifetime could reach 100 years. Consider, for example, the ENHS. The reactor module is to be replaced, according to the design, every 20 EFPY. The steam generators are very simple to replace, if needed (See Secs. 3.4 and 4.2).

11. Investment Protection

In the United States, one of the major factors behind the lack of orders of NPP during the last thirty or so years has been the investment risk. What largely contributed to this risk is the large run over in construction time and cost of many large NPP. Use of small, highly modular NPP with a large component of factory fabrication, assembly and quality assurance greatly reduces this risk.

Another attribute of SIRs that contributes to investment protection is their superb safety. As stated in Sec. 5, SIRs can be designed such that no conceivable accident can damage their fuel or structure. This enhanced safety feature protects the investors in addition to protecting the public.

12. Cost Effective Approach to Technology Development

The development path for any new power reactor system is dependent on the system complexity, safety characteristics, and the number of new components and materials used. The LWR power plants, large fast breeder reactor development and the large gas cooled reactor development programs have used a sequence of reactor development projects, starting small and increasing in size, to arrive at a standard product. This was considered necessary to reduce the incremental development cost and reduce the risk. This approach is both time-consuming and expensive. By virtue of their size and safety characteristics, SIRs can support an alternative approach that features much reduced development time and cost.

SIR concepts that use proven materials can be designed prototypically using computer based methods for design and analysis. This approach is similar to that used in the commercial aircraft industry. The system tested is essentially identical to the system produced in the factory. If, in addition, the SIR design incorporates safety characteristics that permit full-scale demonstration that the reactor maintains its integrity for a broad spectrum of postulated accidents, than the development time and time for reactor certification could be significantly reduced.

This design and testing approach, when integrated with a revised regulatory process could provide both reduced development cost and improved confidence in safety. The revised regulatory process would require interactions between the designer and regulator to not only establish the safety design features but a scope of testing that would be used to demonstrate the capability of the system to tolerate an extreme spectrum of postulated failures. Safety concerns of the regulatory agencies and public critics of nuclear power should be reduced with the increased confidence provided through such an experimental demonstration.

Thus instead of a sequence of reactor tests of increasing size, there would be a need for a single system test that, when coupled with appropriate changes to the licensing and regulation, would support a design certification. Such a result could be achieved at a small fraction of the cost and time required for the sequence of tests usually required to fully demonstrate the safety and reliability of large-scale nuclear power plants. A guesstimate of the cost of applying such an approach to the four technologies discussed in previous sections is summarized in Table 6. There is of course a high level of uncertainty associated with these guesstimates and they will depend heavily on the programmatic objectives.

Table 6. Approximate Estimate of SIR Development Costs
(millions of dollars)

	Coolant type			
	Water	He	Sodium	Pb or Pb-Bi
Components	50-100	200	50-100	500
Prototype Test	[a]	1200	1000	1500

[a] Westinghouse does not plan for a prototype for IRIS and plans to proceed directly to a first-of-a-kind design supported by confirmatory tests. The purpose of the confirmatory tests is to confirm the new design choices. As the major design choices have to do with the integrated heat transport system, the confirmatory tests will consider primarily the thermal-hydraulic behavior of components and systems and can be carried out in experimental loops using electric heaters.

13. Economic Viability

The most uncertain characteristic of SIRs is their economic viability, as no SIR has been constructed, yet. Nevertheless, SIRs have certain attributes that might make them economically viable. These attributes include the following:

1. Simple design with fewer components.
2. Long-life core.
3. Long-life plant.
4. Low operation and maintenance cost.
5. Short construction time.
6. Good match between demand and supply.

7. Factory assembly-line fabrication.
8. Small transmission costs.

Companion papers[20,22,23] address the economic implications of attributes 5 to 8. In the following we'll elaborate on attributes 1 to 4.

The contribution of the design simplification to the plant economics was illustrated in the specific-weight comparison of Table 3. Figure 9 compares the specific capital cost (dollars per installed kW_e) of a 4S reactor, relative to the specific capital cost of a large capacity LWR (the 100% mark). This cost estimate was done by the CRIEPI-TC Japanese economy. The specific capital cost of the first 4S reactor (First-of-a- kind, or FOAK) is high. But the specific capital cost of a mass produced reactor is competitive with that of LWR. Operation and maintenance costs (not shown in the figure) of the 4S reactor are expected to be lower. The long core life of certain SIRs implies a potentially significant increase in the availability of the reactor and, hence, in the attainable plant capacity factor. A dominant fraction of the cost-of-electricity (COE) is inversely proportional to the plant capacity factor. In addition, long core life implies a reduction in the operation and maintenance cost.

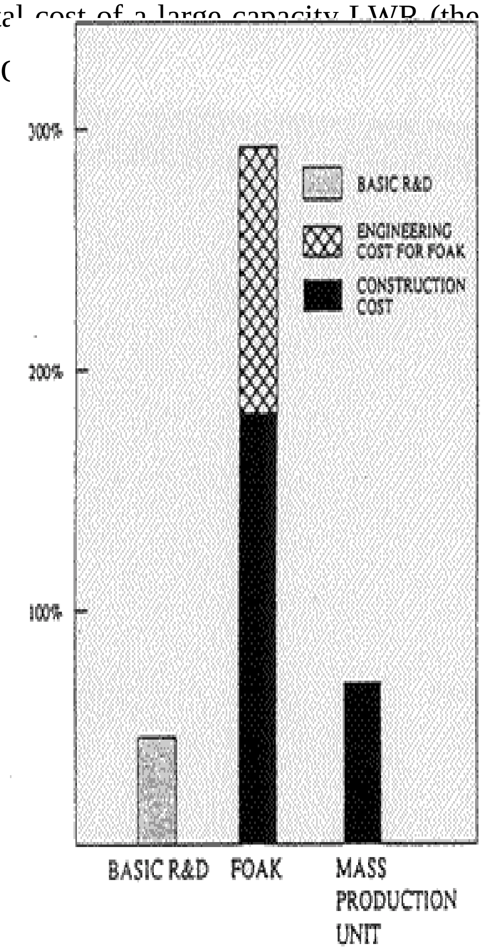

Fig. 9 Estimated Specific Capital Cost of a First-of Its-Kind and of a Mass Produced 4S Reactor

The plant life of certain SIRs, such as the ENHS, could be extremely long – possibly 100 years (see Sec. 10). The lead or lead-bismuth that serve as the coolant can be reused for hundreds of years. The longer the plant life the smaller becomes the capital cost component of the COE and, thus, the more economically viable the plant is. The relative small staff that is required for operating SIRs, as described in Sec. 6, directly implies low operation and maintenance cost.

The relative small staff that is required for operating SIRs, as described in Sec. 6, directly implies low operation and maintenance cost. The expenses associated with the decommissioning of SIR NPPs are also expected to be smaller, on per installed kilowatt basis, than those of large capacity NPP. In the IRIS reactor, for example, the radioactivity level at the end-of-life of the reactor vessel could be orders of magnitude smaller than the corresponding level of radioactivity of conventional PWR vessels. This is due to a combination of relatively low power density along with a large distance between the core and the reactor vessel. The size of this distance is dictated by the inclusion of steam-generators within the vessel. Consider, as another example, the ENHS reactor. The majority of the radioactivity will be formed within the ENHS module. But the ENHS module is designed to be replaced every 20 EFPY. Thus a major part of the decommissioning will be done along with the refueling.

14. Present State of Development

The state of development of the four categories of reactors discussed in the previous sections varies because of previous development efforts that were completed in support of large reactors. In the case of LWRs such as IRIS, there is not only R&D completed but also a large base of commercial and regulatory experience has been accumulated. There is also a great deal of experience with gas-cooled reactors, although, with the exception of those used in Great Britain, there is not a substantial commercial experience. A similar level of development experience is available on sodium cooled fast reactors but there is essentially no commercial experience. The experience on heavy liquid metals is limited to that available from development and operation of the Russian Alpha class submarines.[26] Table 7 provides a comparison summary of the experience accumulated so far with the four reactor technologies. Although there is a wide variation in the status of development of the different reactor types, most of the SIRs being considered would require construction and testing of a prototype to precede commercialization. This is necessary because all of the concepts introduce untested innovative features into their designs. Some of these are important to the safety and therefore take on added importance. In the following we'll elaborate on the development status of few reference SIRs.

Table 7. Experience Gained with Various Reactor Technologies

Technology	Experience	Extent of SIR innovations proposed
LWR	1000's of reactor operating years	Integrated compact designs within current materials experience. Some component innovations to support compactness.
He Cooled GT	10's of reactor operating years	Reactor designs within current, but limited, experience. Innovative power conversion technology with little related experience.
Sodium Cooled	100's of reactor operating years	Integrated compact designs within current operating and materials experience. Some component innovations to support compactness.
Pb or Pb-Bi Cooled	10's of Pb-Bi reactor operating years in Russia	Innovative, integrated compact designs with new components and structural materials.

14.1 IRIS

IRIS relies on proven LWR technology and thus does not need construction of a prototype. The first IRIS reactor will be used for confirmatory testing to prove the safety-by-design features of IRIS that is characterized by a vessel/containment design that is thermo-hydraulically coupled. The extended maintenance features of IRIS – once every 4 years, will have to undergo confirmatory testing as well. Integral steam generators of the type to be installed in IRIS have been fabricated and tested by Ansaldo, one of IRIS team members. The first IRIS reactor will use a less than 5% enriched fuel, thus will require no special fuel development and licensing. Future reload cores will use 8 to 10 % enriched fuel, which will require in-pile testing and licensing. This is planned to be done in the 2015-2020 time frame. IRIS currently features conventional control rods, but plans to install internal drive mechanisms which, while currently in use or under design in several advanced reactors, will need ad hoc testing.

14.2 PBMR and GT-MHR

The two gas cooled SIRs under development, the PBMR and the GT-MHR, have a similar level of R&D and operational experience to support them. They are both using very similar fuel that has been used in reactor operations. In fact, they have taken the approach of avoiding changes to this fuel in order to rely on extensive development that has been completed in Europe and the U.S. The largest development uncertainty is in the unique power conversion systems being proposed. Both concepts use direct cycle helium turbines to drive the generators. This design dramatically reduces the amount of equipment. However, the turbines and generators are to operate in a vertical orientation and use magnet bearings. No commercial experience exists with vertically oriented turbo-generators of the size required. The reactor also uses helium-to-water and helium-to-helium heat exchangers. These components will need to be tested, possibly in special feature tests prior to testing in a prototype.

Some additional testing will be required for the PBMR. These include testing of the on-line fuel monitoring and recycling systems as well as testing of the core power monitoring and control systems. Quality manufacturing of the fuel kernels and adequate containment of certain fission products need be demonstrated as well.

Although these reactors do not introduce any new material, they do make claim to certain inherent safety features that they will need to demonstrate before getting regulatory approval. The passive cooling and inherent shutdown in unprotected accidents will need to be demonstrated in the prototype and it is possible that some feature testing of the fuel for these conditions will be conducted.

14.3 4S and ENHS

There is a large range of innovation used in the liquid metal reactors (LMRs). Particularly when it comes to use of heavy liquid metals such as lead and lead-bismuth rather than sodium, which has been used extensively. The small sodium cooled reactors have a very large experience base supporting their development. And in the case of 4S many components, such as the electromagnetic pump, have or are being tested. The core designs for the sodium-cooled concepts use proven fuel materials. It can be expected that a very innovative concept like ENHS will require an extensive component development program and features testing. Some of the feature tests will need to be completed simply to confirm the capability to fabricate the design. On the other hand, a reactor like 4S has a design that is reasonably developed with no questions about feasibility of its construction.

Any heavy metal cooled system introduces a large change in the development requirements simply because of the minimal experience that exists outside of Russia. The cost of establishing an experience base outside Russia is a major addition to development, even in the case of L4S. The key questions that need to be answered are related to the control of the coolant corrosion of the structural materials. The Russians claim that they have solved all these material related problems for lead-bismuth coolant. Initial independent research activities carried out in recent years outside Russia tends to confirm that there are relatively simple effective means to overcome the corrosion problem. Nevertheless, a much more extensive R&D need be pursued. Such an R&D is quite common in the nuclear industry. Thus, for example, in their early days of development LWRs faced severe corrosion problem. Subsequent R&D carried-out by the U.S. Naval program under Admiral Rickover came up with a simple but effective solution involving careful water chemistry control.

It is possible to conceive LMR-SIRs whose development requirements are not substantially different in magnitude than those of either gas or water-cooled systems. However, as one introduces the innovative features needed to achieve the desirable objectives of Generation IV systems, development needs become more extensive. For example, designs that seek to use natural circulation introduce additional development needs.

14.4 Fuel Cycles

The fuel cycles for the LWRs and gas cooled SIRs are expected to be once-through and therefore do not introduce major development efforts in the area of the fuel cycle beyond those associated with the current generation of reactors. There is uncertainty associated with the form of waste disposal of the gas-cooled reactor fuel, but this is not likely to be a major technical problem. In the case of LMRs, it is almost certain that they must recycle the fuel, which adds a development issue not present in the water and gas cooled reactors. The certainty in this statement is the result of the relatively high enrichment that remains in the spent fuel, making it a valuable resource. This may change if very high fuel burnups can be achieved. Otherwise there is a need to select and complete the development of a preferred process for recycling the fuel. This must be done to complete commercialization.

A number of innovative processes have been developed, at least partially, for recycling the fuel of liquid metal reactors in a proliferation resistant manner. The most well known and well developed of these processes is the IFR (Integrated Fast Reactor) process. Details about this process can be found in Ref. 27.

15. R&D to Commercialization

Section 14 outlined the type of R&D required for completing the development and testing of selected SIRs. This is the major part of the R&D needed for commercialization. However, there is a need to also give attention to development of manufacturing and transportation elements of small reactors. In order to achieve commercial competitiveness it is necessary for the small reactors to be produced, delivered, installed and removed at the site with methods quite different than currently used in large plants. Without major economic gains in these areas as a result of the changes in the way business is conducted it is unlikely that SIRs will be competitive. Therefore there is development work required in the area of the supporting infrastructure. It potentially includes equipment to manufacture (for example robots), ship and install the integrated reactor package.

16. Summary and Recommendation

Relative to large power reactors, SIRs have a number of attributes that could make them a preferred source of nuclear energy for certain applications, such as in developing countries. The attributes of SIRs include the following:

- Reduced number of components and design simplicity.
- High degree of modularity; the modules are completely fabricated and assembled in factory.
- Elimination of severe accidents by design leading to enhanced safety.
- Simplified operation and maintenance.
- Enhanced proliferation resistance.
- Close match between demand and supply of electricity.
- Short construction time.
- Long plant life.
- Investment protection.
- Cost effective approach to technology development.

Although the economic viability of SIRs has not yet been proven, there is basis to expect that it could be realized.

SIRs appear to be particularly attractive for developing countries as they can offer long-term energy security (due to the very long life cores they can have) with very high level of proliferation resistance along with superb safety and relative ease of operation and maintenance. The SIRs can be deployed as distributed energy sources in regions that lack central transmission lines. Nevertheless, multi-SIR power plants may be attractive also in industrial countries. Hence, it is recommended that a thorough examination of the desirability of SIR development to commercialization be undertaken.

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